Draft Recommended Practice for Calculating AC Short-Circuit Currents in Industrial and Commercial Power Systems
Violet Book

Sponsor

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Draft Recommended Methods for Calculating AC Short-Circuit Currents in Industrial and Commercial Power Systems

Chapter 1

Overview

1.1 Scope

Electric power systems in industrial plants, commercial and institutional buildings are designed to serve loads in a safe and reliable manner. One of the major considerations in the design of a power system is adequate control of short-circuits or faults as they are commonly called. Uncontrolled short-circuits can cause service outage with accompanying production downtime and associated inconvenience, interruption of essential facilities or vital services, extensive equipment damage, personnel injury or fatality, and fire damage.

Short-circuits are caused by faults in the insulation of a circuit, and in many cases an arc ensues at the point of the fault. Such an arc may be destructive and may constitute a fire hazard. Prolonged duration of arcs, in addition to the heat released, may result in transient overvoltages which may endanger the insulation of equipment in other parts of the system. Clearly, the fault must be quickly removed from the power system, and this is the job of the circuit protective devices—the circuit breakers and fusible switches.

A short-circuit current generates heat which is proportional to the square of the current magnitude, I^2R. The large amount of heat generated by a short-circuit current may damage the insulation of rotating machinery and apparatus which is connected into the faulted system, including cables, transformers, switches, and circuit breakers. The most immediate danger involved in the heat generated by short-circuit currents is permanent destruction of insulation. This may be followed by actual fusion of the conducting circuit, with resultant additional arcing faults.

The heat which is generated by high short-circuit currents tends not only to impair insulating materials to the point of permanent destruction, but also exerts harmful effects upon the contact members in interrupting devices.

The small area common between two contact members which are in engagement depends mainly upon the hardness of the contact material and upon the amount of pressure by which they are kept in engagement. Owing to the concentration of the flow of current at the points of contact engagement, the temperatures of these points reached at the times of peak current are very high. As a result of these high spot temperatures, the material of which the contact members are made may soften. If, however, the contact material is caused to melt by excessive I^2R losses, there is an imminent danger of welding the contacts together rendering it impossible to separate the contact members when the switch or circuit breaker is called upon to open the circuit. Since it requires but very little time to establish thermal equilibrium at the small points of contact engagement, the temperature at these points depends more upon the peak current than upon the rms current.

If the peak current is sufficient to cause the contact material to melt, resolidification may occur immediately upon decrease of the current from its peak value.

Other important effects of short-circuit currents are the strong electromagnetic forces of attraction and repulsion to which the conductors are subjected when short-circuit currents are present. These forces are proportional to the square of the current and may subject any rotating machinery and transmission and switching equipment to severe mechanical stresses and strains. The strong electromagnetic forces which high short-circuit currents exert upon equipment can cause deformation in rotational machines, transformer windings, and equipment bus bars, which may fail at a future time. Deformation in breakers and switches will cause alignment and interruption difficulties.

Modern interconnected systems involve the operation in parallel of large numbers of synchronous machines, and the stability of such an interconnected system may be greatly impaired if a short-circuit in any part of the system is allowed to prevail. The stability of a system requires short fault clearing times and can be more limiting than the longer time considerations imposed by thermal or mechanical effects on the equipment.

1.2 Definitions

The following are the definitions of terms commonly used on the subject of short circuits and used in the following chapters.

1.2.1 arcing time: The interval of time between the instant of the first initiation of the arc and the instant of final arc extinction in all poles.

1.2.2 armature: The main current carrying winding of a machine. Usually the stator.

1.2.3 armature resistance: R_a - The direct current armature resistance. This is determined from a dc resistance measurement. The approximate effective ac resistance is 1.2*R_a.

1.2.4 available current: The current that would flow if each pole of the breaking device under consideration were replaced by a link of negligible impedance without any change of the circuit or the supply.

1.2.5 asymmetrical current: The combination of the symmetrical component and the direct current component of the current.

1.2.6 breaking current: The current in a pole of a switching device at the instant of the arc initiation. Better known as “Interrupting Current.”

1.2.7 clearing time: The total time between the beginning of specified overcurrent and the final interruption of the circuit at rated voltage. In regard to fuses, it is the sum of the minimum melting time of a fuse plus tolerance and the arcing time. In regard to breakers under 1000 volts, it is the sum of the sensor time, plus the opening time and the arcing time. In regard to breakers over 1000 volts, it is sum of the minimum relay time (usually 1/2 cycle), plus the contact parting time and the arcing time. It is sometimes referred to as “Total Clearing Time” or “Interrupting Time.”

1.2.8 close and latch: The capability of a switching device to close (allow current flow) and immediately thereafter latch (remain closed) and conduct a specified current through the device under specified conditions.

1.2.9 close and latch duty: The maximum rms value of calculated short-circuit current for medium and high voltage circuit breakers during the first-cycle with any applicable multipliers for fault current X/R ratio. Often the close and latching duty calculation is simplified by applying a 1.6 factor to the calculated

breaker first cycle symmetrical ac rms short-circuit current. Also called first cycle duty (formerly momentary duty).

1.2.10 close and latch rating: The maximum current capability of a medium or high voltage circuit breaker to close and immediately thereafter latching closed for normal-frequency making current. The close and latching rating is 1.6 times the breaker rated maximum symmetrical interrupting current in ac rms amperes or a peak current which is 2.7 times ac rms rated maximum symmetrical interrupting current. Also called first cycle rating, (formerly momentary rating).

1.2.11 circuit breaker: A switching device capable of making, carrying, and breaking currents under normal circuit conditions and also making, carrying for a specified time, and breaking currents under specified abnormal conditions such as those of short circuit.

1.2.12 contact parting time: The interval between the time when the actuating quantity in the release circuit reaches the value causing actuation of the release and the instant when the primary arcing contacts have parted in all poles. Contact parting time is the numerical sum of release delay and opening time.

1.2.13 crest current: The highest instantaneous current during a period. It is the same as peak current.

1.2.14 direct axis: The machine axis which represents a plane of symmetry in line with the no-load field winding.

1.2.15 direct axis substranient reactance: X''_{dv} - (saturated, rated voltage) is the apparent reactance of the stator winding at the instant short-circuit occurs with the machine at rated voltage, no load. This reactance determines the current flow during the first few cycles after short-circuit.

1.2.16 direct axis subtransient reactance: X''_{di} - (unsaturated, rated current) is the reactance which is determined from the ratio of an initial reduced voltage open circuit condition and the currents from a three-phase fault at the machine terminals at rated frequency. The initial open circuit voltage is adjusted so that rated current is obtained. The impedance is determined from the currents during the first few cycles.

1.2.17 direct axis transient reactance: X'_{di} - (unsaturated, rated current) is the reactance which is determined from the ratio of an initial reduced voltage open circuit condition and the currents from a three-phase fault at the machine terminals at rated frequency. The initial open circuit voltage is adjusted so that rated current is obtained. The initial high decrement currents during the first few cycles are neglected.

1.2.18 direct axis transient reactance: X'_{dv} - (saturated, rated voltage) is the apparent reactance of the stator winding several cycles after initiation of the fault with the machine at rated voltage, no load. The time period for which the reactance may be considered $\mathrm{X}'_{\mathrm{dv}}$ can be up to a half (1/2) second or longer, depending upon the design of the machine and is determined by the machine direct-axis transient time constant.

1.2.19 fault: A current that flows from one conductor to ground or to another conductor owing to an abnormal connection (including an arc) between the two. It is the same as “Short Circuit.”

1.2.20 fault point X/R: The calculated fault point X/R ratio using separate reactance and resistance networks.

1.2.21 fault point angle: The calculated fault point angle (Tan^{-1}(X/R ratio) using complex ($R + jX$) reactance and resistance networks for the X/R ratio.

1.2.22 field: The exciting or magnetizing winding of a machine.

1.2.23 first cycle duty: The maximum value of calculated short-circuit current for the first cycle with any applicable multipliers for fault current X/R ratio.

1.2.24 first cycle rating: The maximum current capability of a piece of equipment during the first cycle of a fault.

1.2.25 frequency: The rated frequency of a circuit.

1.2.26 fuse: A device that protects a circuit by melting open its current-carrying element when an overcurrent or short-circuit current passes through it.

1.2.27 impedance: The vector sum of resistance and reactance in an ac circuit.

1.2.28 interrupting current: The current in a pole of a switching device at the instant of the arc initiation. It is sometime referred to as "Breaking Current."

1.2.29 interrupting time: The interval between the time when the actuating device "sees" or responds to an operating value, the opening time and arcing time. It is sometimes referred to as *"total break time"* or *"clearing time."*

1.2.30 maximum rated voltage: The upper operating voltage limit for a device.

1.2.31 minimum rated voltage: The lower operating voltage limit for a device where the rated interrupting current is a maximum. Operating breakers at voltages lower than minimum rated voltage restricts the interrupting current to maximum rated interrupting current.

1.2.32 momentary current duty: See presently used terminology of *"close and latch duty."* Used for medium and high voltage breaker duty calculations for breakers manufactured before 1965.

1.2.33 momentary current rating: The maximum rms current measured at the major peak of the first cycle, which the device or assembly is required to carry. Momentary rating was used on medium and high voltage breakers manufactured before 1965. See presently used terminology of *"close and latch rating."*

1.2.34 negative sequence: A set of symmetrical components that have the angular phase lag from the first member of the set to the second and every other member of the set equal to the characteristic angular phase difference and rotating in the reverse direction of the original vectors. For a three-phase system, the angular different is 120 degrees. *Also see* **"symmetrical components."**

1.2.35 negative sequence reactance: X_{2v} - (saturated - rated voltage) The rated current value of negative-sequence reactance is the value obtained from a test with a fundamental negative-sequence current equal to rated armature current. The rated voltage value of negative-sequence reactance is the value obtained from a line-to-line short-circuit test at two terminals of the machine at rated speed, applied from no load at rated voltage, the resulting value being corrected when necessary for the effect of harmonic components in the current.

1.2.36 offset current: A current waveform whose baseline is offset from the ac symmetrical current zero axis.

1.2.37 opening time: The time interval between the time when the actuating quantity of the release circuit reaches the operating value, and the instant when the primary arcing contacts have parted. The opening time includes the operating time of an auxiliary relay in the release circuit when such a relay is required and supplied as part of the switching device.

1.2.38 peak current: The highest instantaneous current during a period.

1.2.39 positive sequence: A set of symmetrical components that have the angular phase lag from the first member of the set to the second and every other member of the set equal to the characteristic angular phase

difference and rotating in the same phase sequence of the original vectors. For a three phase system, the angular different is 120 degrees. *Also see* **"symmetrical components."**

1.2.40 positive sequence machine resistance: R_1 - is that value of rated frequency armature resistance which, when multiplied by the square of the rated positive-sequence armature current and by the number of phases is equal to the sum of the copper loss in the armature and the load loss resulting from the flow of that current. This is not the resistance to be used for the machine in short-circuit calculations.

1.2.41 quadrature axis: The machine axis which represents a plane of symmetry in the field which produces no magnetization. This axis is 90 degrees ahead of the direct axis.

1.2.42 quadrature axis subtransient reactance: X''_{qi} - (unsaturated, rated current) same as X''_{di} except in quadrature axis.

1.2.43 quadrature axis subtransient reactance: X''_{qv} - (saturated, rated voltage) same as X''_{dv} except in quadrature axis.

1.2.44 quadrature axis transient reactance: X_q - (unsaturated, rated current) is the ratio of reactive armature voltage to quadrature-axis armature current at rated frequency and voltage.

1.2.45 quadrature axis transient reactance: X'_{qv} - (saturated, rated voltage) same as X'_{dv} except in q quadrature axis.

1.2.46 quadrature axis transient reactance: X'_{qi} - (unsaturated, rated voltage) same as X'_{di} except in quadrature axis.

1.2.47 rating: The designated limit(s) of the operating characteristic(s) of a device. This data is usually on the device nameplate.

1.2.48 rms: The square root of the average value of the square of the voltage or current taken throughout one period. In this text rms will be considered total rms unless otherwise noted.

1.2.49 rms, ac: The square root of the average value of the square of the ac voltage or current taken throughout one period.

1.2.50 rms, single cycle: The square root of the average value of the square of the ac voltage or current taken throughout one ac cycle.

1.2.51 rms, total: The square root of the average value of the square of the ac and dc voltage or current taken throughout one period.

1.2.52 rotor: The rotating member of a machine.

1.2.53 short-circuit: An abnormal connection (including arc) of relative low impedance, whether made accidentally or intentionally, between two points of different potentials. It is the same as *"fault."*

1.2.54 short-circuit duty: The maximum value of calculated short-circuit current for either first-cycle current or interrupting current with any applicable multipliers for fault current *X*/*R* ratio or decrement.

1.2.55 stator: The stationary member of a machine.

1.2.56 symmetrical: That portion of the total current that constitutes the symmetry.

1.2.57 symmetrical components: A symmetrical set of three vectors used to mathematically represent an unsymmetrical set of three-phase voltages or currents. In a three-phase system, one set of three equal

magnitude vectors displaced from each other by 120 degrees in the same sequence as the original set of unsymmetrical vectors. This set of vectors is called the *positive sequence component*. A second set of three equal magnitude vectors displaced from each other by 120 degrees in the reverse sequence as the original set of unsymmetrical vectors. This set of vectors is called the *negative sequence component*. A third set of three equal magnitude vectors displaced from each other by 0 degrees. This set of vectors is called the *zero sequence component.*

1.2.58 synchronous reactance: Direct axis X_d - (unsaturated, rated current) is the self reactance of the armature winding to the steady-state balanced three-phase positive-sequence current at rated frequency and voltage in the direct axis. It is determined from an initial open-circuit voltage and a sustained short circuit on the asynchronous machine terminals.

1.2.59 three-phase open circuit time constant: T_{a3} - is the time constant representing the decay of the machine currents to a suddenly applied three-phase short-circuit to the terminals of a machine.

1.2.60 total break time: The interval between the time when the actuating quantity of the release circuit reaches the operating value, the switching device being in a closed position, and the instant of arc extinction on the primary arcing contacts. Total break time is equal to the sum of the opening time and arcing time. Better known as "interrupting time."

1.2.61 total clearing time: *See* **"Clearing Time"** or **"Interrupting Time."**

1.2.62 voltage, high: Circuit voltages over nominal 34.5 kV. This may be different than other ANSI definitions.

1.2.63 voltage, low: Circuit voltage under 1000 volts.

1.2.64 voltage, medium: Circuit voltage greater than 1000 volts up to and including 34.5 kV. This may be different than other ANSI definitions.

1.2.65 voltage range factor: The voltage range factor, K, is the range of voltage to which the breaker can be applied where $E * I$ equals a constant. K = maximum rated operating voltage / minimum rated operating voltage.

1.2.66 *X/R* ratio: The ratio of rated frequency reactance and effective resistance to be used for short-circuit calculations. Approximately equal to $X_{2V}/(1.2*R_a)$ or $2\pi f*T_{a3}$.

1.2.67 zero sequence: A set of symmetrical components that have the angular phase lag from the first member of the set to the second and every other member of the set equal to zero (0) degrees and rotating in the same direction as the original vectors. Also see "symmetrical components."

1.2.68 30-cycle time: The time interval between the time when the actuating quantity of the release circuit reaches the operating value, and the approximate time when the primary arcing contacts have parted. The time period considers the ac decaying component of a fault current to be negligible.

1.3 Abbreviations and acronyms

The following are the symbols and their definitions that are used in this book:

a Symmetrical component operator = 120 degrees.

e Instantaneous voltage.

e_o Initial voltage.

E Rms voltage.

Emax Peak or crest voltage.

E_{LN} Rms line to neutral voltage.

E_{LL} Rms line to line voltage.

f Frequency in Hertz.

i Instantaneous current.

i_{dc} Instantaneous dc current.

i_{ac} Instantaneous ac current.

I Rms current.

I**max** Peak or crest current.

$I_{max,s}$ Symmetrical peak current.

$I_{max,ds}$ Decaying symmetrical peak current.

I' Rms transient current.

I'' Rms subtransient current.

I'_{dd} Interrupting duty current.

I''_{dd} First cycle duty current.

I_{SS} Rms steady state current.

j 90 degree rotative operator, imaginary unit

L Inductance.

Q Electric Charge

R Resistance.

R_a Armature resistance.

T_{a3} Three-phase open-circuit time constant.

t Time

X Reactance.

X_d' Transient direct-axis reactance.

X_d'' Subtransient direct-axis reactance.

$\boldsymbol{X_q}'$ Transient quadrature-axis reactance.

$\boldsymbol{X_q}''$ Subtransient quadrature-axis reactance.

$\boldsymbol{X_{2V}}$ Negative sequence rated voltage.

$\boldsymbol{Z}$ Impedance: $Z = R + jX$.

α $\mathrm{Tan}^{-1}(\omega L/R = \tan^{-1}(X/R)$.

ϕ Phase angle.

ω Angular frequency $\omega = 2\pi f$.

τ Intermediate time.

θ Phase angle difference.

1.4 References

This chapter shall be used in conjunction with the following publications. If the following are superseded by an approved revision, the revision shall apply.

ANSI/IEEE Std 260.1-1993, American National Standard Letter Symbols for Units of Measurement.
IEEE Std 91-1984, IEEE Standard Graphic Symbols for Logic Diagrams.[1]
IEEE Std 100-1996, IEEE Standard Dictionary of Electrical and Electronics Terms, Sixth Edition.
IEEE Std 141-1993, IEEE Recommended Practice for Electric Power Distribution of Industrial Plants (*IEEE Red Book*).
IEEE Std 142-1991, IEEE Recommended Practice for Grounding of Industrial and Commercial Power Systems (*IEEE Green Book*).
IEEE Std 241-1990 (R1997), IEEE Recommended Practice for Electric Power Systems in Commercial Buildings (*IEEE Gray Book*).
IEEE Std 242-1991, IEEE Recommended Practice for Protection and Coordination of Industrial and Commercial Power Systems (*IEEE Buff Book*).
IEEE Std 280-1985 (R1997), IEEE Standard Letter Symbols for Quantities Used in Electrical Science and Electrical Engineering.
IEEE Std 315-1975 (R1993), IEEE Graphic Symbols for Electrical and Electronics Diagrams.
IEEE Std 399-1997, IEEE Recommended Practice for Industrial and Commercial Power Systems Analysis (*IEEE Brown Book*).
IEEE Std 446-1995, IEEE Recommended Practice for Emergency and Standby Power Systems for Industrial and Commercial Applications (*IEEE Orange Book*).
IEEE Std 493-1997, IEEE Recommended Practice for the Design of Reliable Industrial and Commercial Power Systems (*IEEE Gold Book*).
IEEE Std 602-1996, IEEE Recommended Practice for Electric Systems in Health Care Facilities (*IEEE White Book*).
IEEE Std 739-1995, IEEE Recommended Practice for Energy Management in Industrial and Commercial Facilities (*IEEE Bronze Book*).
IEEE Std 1100-1992, IEEE Recommended Practice for Powering and Grounding Sensitive Electronic Equipment (*IEEE Emerald Book*).
IEEE Std SI 10-1997, (IEEE/ASTM) Standard for Use of the International System of Units (SI)—The Modern Metric System.

[1] IEEE publications are available from the Institute of Electrical and Electronics Engineers, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA (http://www.standards.ieee.org/).

1.5 Manufacturers' Data Sources

The last chapter in this reference book contains a collection of data from various manufacturers. While reasonable care was used to compile this data, equipment with the same identification and manufactured during different periods may have different ratings. The equipment nameplate is the best source of data and may require obtaining the serial number and contacting the manufacturer.

The electrical industry, through its associations and individual manufacturers of electrical equipment, issues many technical bulletins and data books. While some of this information is difficult for the individual to obtain, copies should be available to each major design unit. The advertising sections of electrical magazines contain excellent material, usually well-illustrated and presented in a clear and readable form, concerning the construction and application of equipment. Such literature may be promotional; it may present the advertiser's equipment or methods in a best light and should be carefully evaluated. Manufacturers' catalogs are a valuable source of equipment information. Some of the larger manufacturers' complete catalogs are very extensive, covering dozens of volumes; however, these companies may issue abbreviated or condensed catalogs that are adequate for most applications. Data sheets referring to specific items are almost always available from the sales offices. Some technical files may be kept on microfilm at larger design offices for use either by projection or by printing. Manufacturers' representatives, both sales and technical, can do much to provide complete information on a product.